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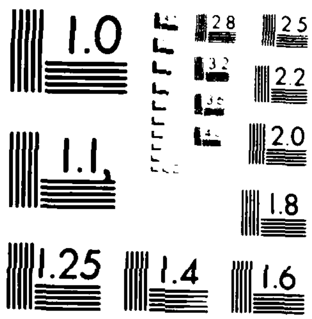

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DECISION FEEDBACK EQUALIZER TEST RESULTS FOR HF SKYWAVE COMMUNICATIONS

Design trade-offs and performance data are presented for Kalman and LMS-decision feedback equalizers

LE Hoff
AR King

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Simulation results which address the design trade-offs of Decision Feedback Equalizers (DFE) using the Kalman and LMS algorithms are presented. Test results are given on varying the transmitted reference, equalization loop bandwidth, equalizer tap positioning, and synchronization. The DFE performance on fading multipath channels is compared to switching diversity and the impact of path separation is shown. Performance results are given for both simulated and measured HF channels. Simulation results show that the Kalman DFE performs as well or better than the LMS DFE or parallel tone modems and out performs them when there are multiple fading signal skywave paths.

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1.0 INTRODUCTION

The purpose of this report is to present some additional results on the Decision Feedback Equalizer (DFE) which were not covered by NOSC TR 709.[1] This document was written to augment TR 709 and should be read in conjunction with it. The data presented should be useful to those who are interested in the design of adaptive equalizers for HF. This material addresses HF channel equalizer design and performance.

In section 2 we examine some of the design trade-offs of the DFE. For a given channel multipath structure and fade rate, there is an optimum choice of the number of equalizer taps and loop bandwidth. However, at HF the very wide range of channel conditions which exist makes the choice of equalizer parameters difficult. A compromise design must be made that will be good for most channels. The results in section 2 should be helpful in making such compromises.

In section 3 the performance of the DFE on multipath channels is examined. In section 3.1 the bit error rate on multipath fading channels is compared to diversity switching. In section 3.2 the problem of path resolution is examined. Multipath signals separated by less than one bit period result in higher bit error rates than channels with path separations greater than a bit period. This suggests that, within limits, there may be some advantages to using wider bandwidth signals.

Section 4 compares the Kalman and LMS DFE algorithms on measured HF channels. In 4.1 channel parameters measured are used to compare algorithms' performances over long distance paths.[2] In section 4.2 actual recorded HF signals from a short range path are evaluated. Several cases are presented

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[1] NOSC TR 709, Skywave Communication Techniques, Decision Feedback Equalization for Serially Modulated Spread-spectrum Signals in the HF Band Yields Improved Reliability, by LE Hoff and AR King, p 54, 30 March 1981.

[2] Watterson, CC, Juroshek, JR, and Bensema, WD, Experimental Confirmation of an HF Channel Model in IEEE Transactions on Communications Technology, vol 1, COM-18, No 6, p 792-803, Dec 1970.

showing a wide range of performance results.[3] The Kalman DFE consistently performed as well or better than the LMS DFE or the parallel tone modems on fading channels.

[3] NOSC TR 727, Maximum Likelihood Sequence Estimation For Unknown, Dispersive, and Time Variant Communication Channels, p 48, 30 Sept 1981.

2.0 DESIGN TRADE-OFFS

The performance of the Kalman and LMS Decision Feedback Equalizer is a function of many factors, including: filter loop bandwidth, signal-to-noise ratio, rates of fading of the skywave paths, bit sample rate, the number of fading paths, the number and position of the taps on the channel equalizer delay line, the percentage of the time that reference is being transmitted, the length of the reference segments, and undoubtedly other things not examined.

2.1 TRANSMITTED REFERENCE SIGNALS

The Kalman DFE equalizer is identical to the LMS equalizer except for the algorithm by which the weights are updated and the way in which the reference is inserted into the data. Differences in use of references are:

1. The LMS equalizer was simulated with information on the "I" channel and reference on the "Q" channel.

2. The Kalman algorithm was simulated with reference and information time multiplexed so that there is either all reference or all information on both the "I" and "Q" channels.

If the Kalman DFE receiver could be operated totally decision directed, it would be possible to transmit an average of two bits per sample period. But the receiver needs a certain amount of reference directed transmission to accept the weights before one switches to decision directed operation. It was found that once the weights adapted to the point that the error rate was low, 2 bits per sample period could be transmitted using QPSK. There was a problem if there was too much noise or if the channel faded through low SNR conditions, the error rate could jump close to 100%. There are ways to combat this problem, but they all lower the data rate back toward 1 bit per sample period.

2.2 KALMAN AND LMS LOOP BANDWIDTH

The equalizer's loop bandwidth controls the rate of adaptation of the tap weights and is one of the more critical equalizer parameters. The value of loop bandwidth that minimizes the probability of error depends upon the doppler spread, doppler shift, received signal to noise ratio, number of equalizer taps, and for the LMS algorithm, input data eigenvalue spread.

As might have been expected, the more rapidly the channel changes, the larger the equalizer loop bandwidth must be to keep up with the channel (fig 1, LMS). For channels with fading paths the optimal channel equalizer loop bandwidth was found to also increase as the signal-to-noise ratio increased (fig 2, LMS; fig 3, Kalman).

Very important to LMS DFE design is the very rapid drop in allowable equalizer loop bandwidth as the number of equalizer filter taps is increased. To determine the maximum allowable loop bandwidth for a given number of equalizer taps, simulations were run with a single fixed path channel. The results are shown in figures 4 and 5. Two basic points are shown: 1) the lower the bandwidth, the better the performance with a fixed channel; 2) the greater the number of taps, the lower the maximum loop bandwidth. Table 1 summarizes some maximum usable loop bandwidth simulation data. There are limits on the lowest as well as the highest usable equalizer loop bandwidth, even with fixed channels, as the loop bandwidth affects the time it takes for the equalizer to initially converge to the correct values. The number of taps is also important when using Kalman weight adaptation, but we have very limited simulation experience on the subject.

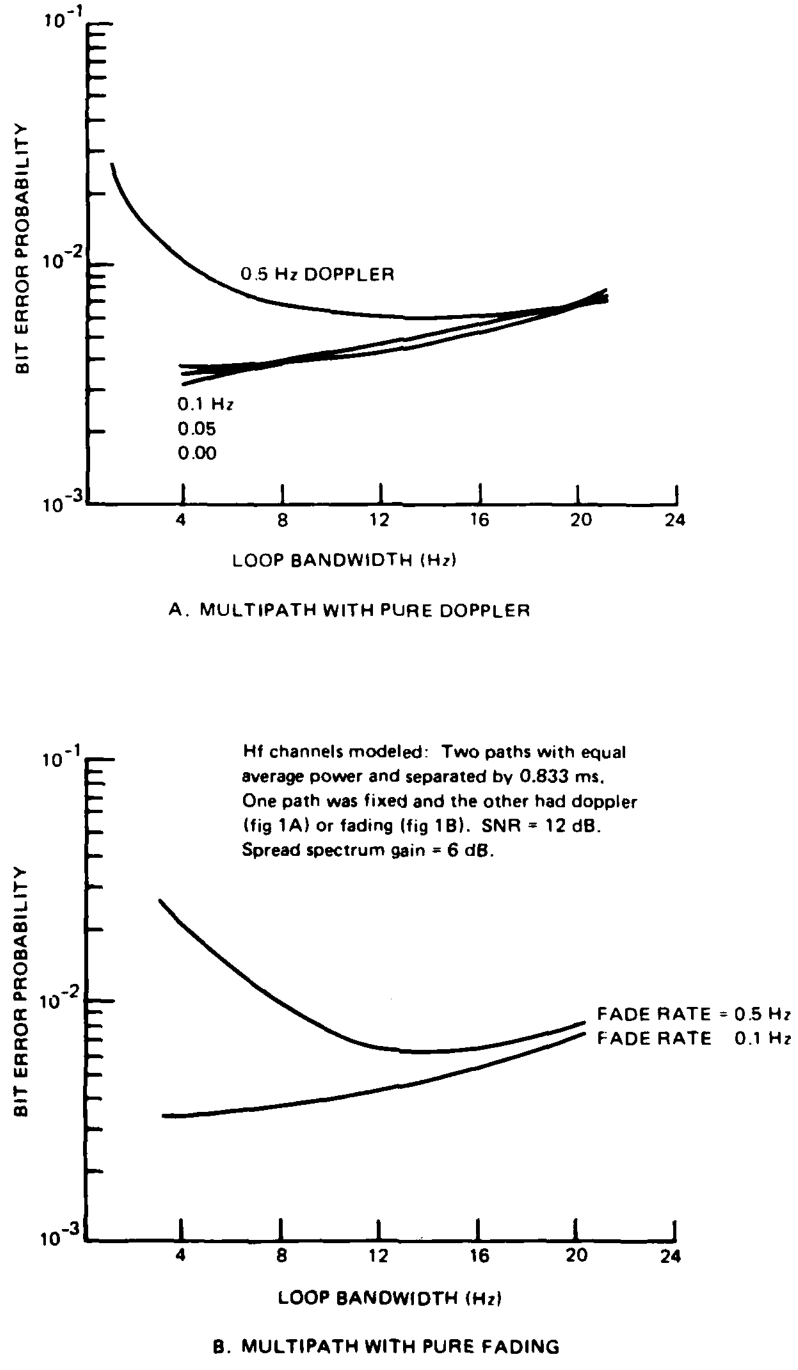

Figure 1. LMS equalizer performance as a function of equalizer loop bandwidth.

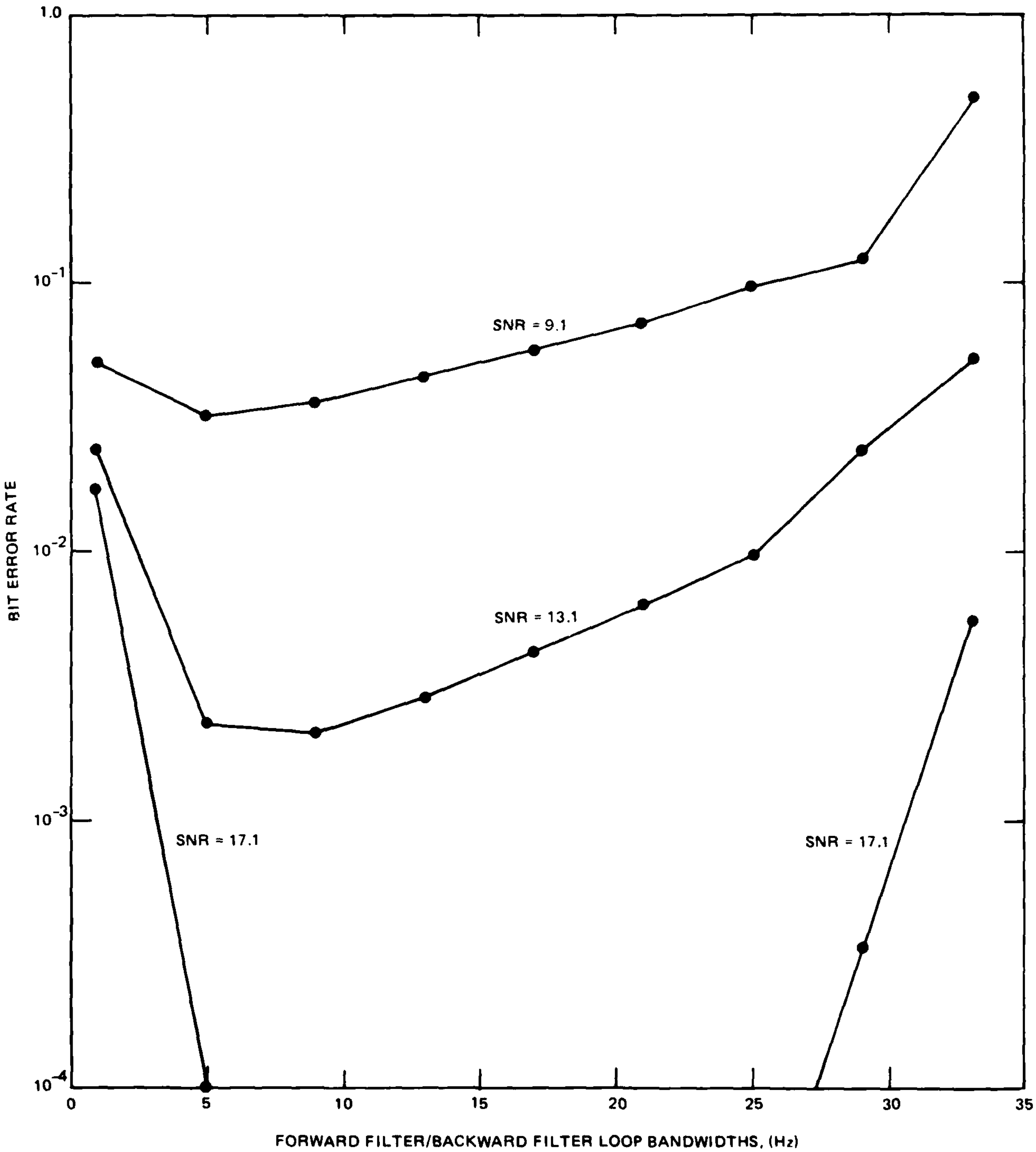

Figure 2. Effects of signal-to-noise ratio and equalizer loop bandwidth on the performance of an equalized receiver using LMS adaptation. Channel: two equal average power paths. One path fixed, other path fading with 1 Hz frequency spread. Equalizer with two forward and four backward taps.

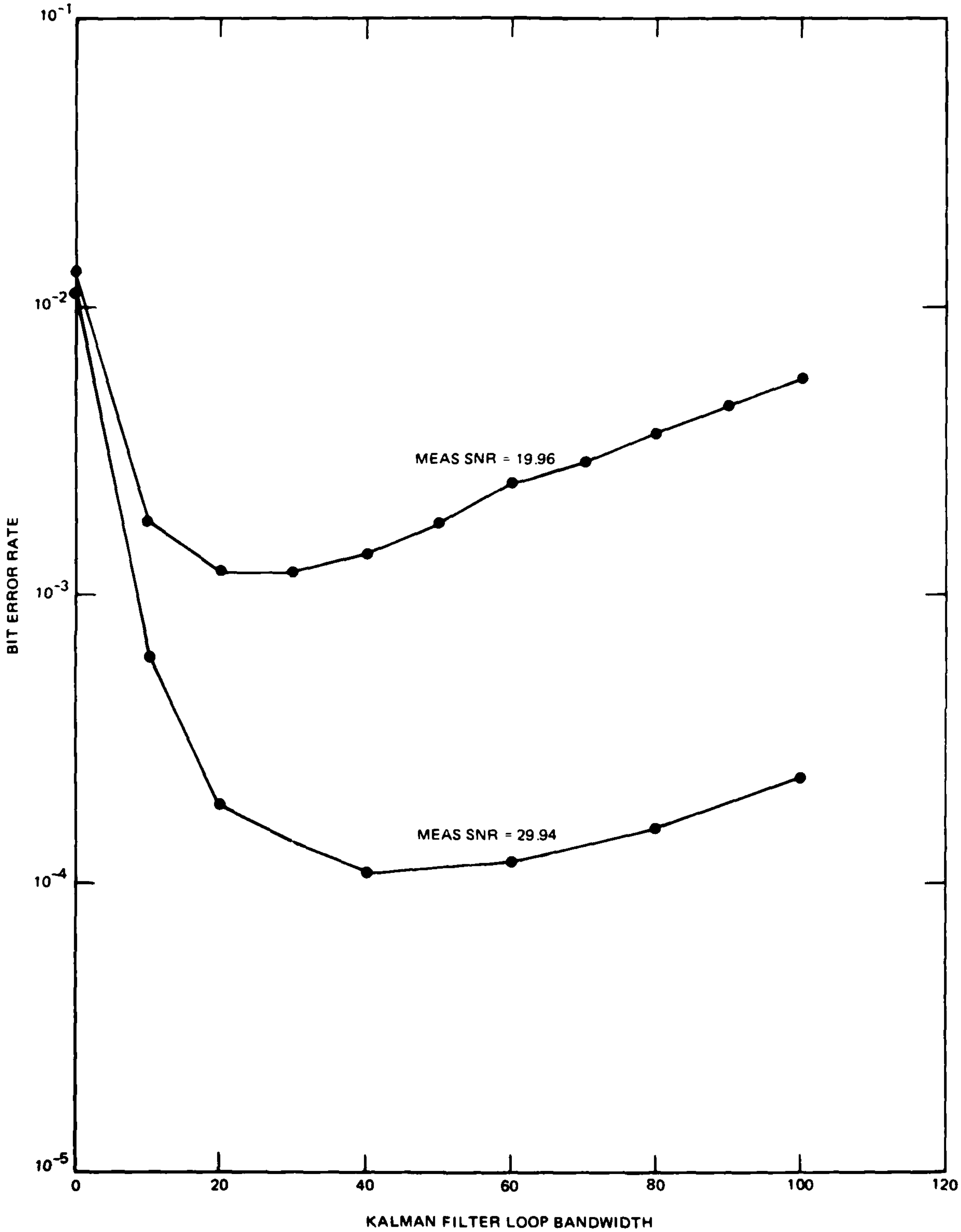

Figure 3. Effects of signal-to-noise ratio and equalizer loop bandwidth on the performance of an equalized receiver using Kalman adaptation. Channel: one path fixed and other path fading with 1 Hz frequency spread.

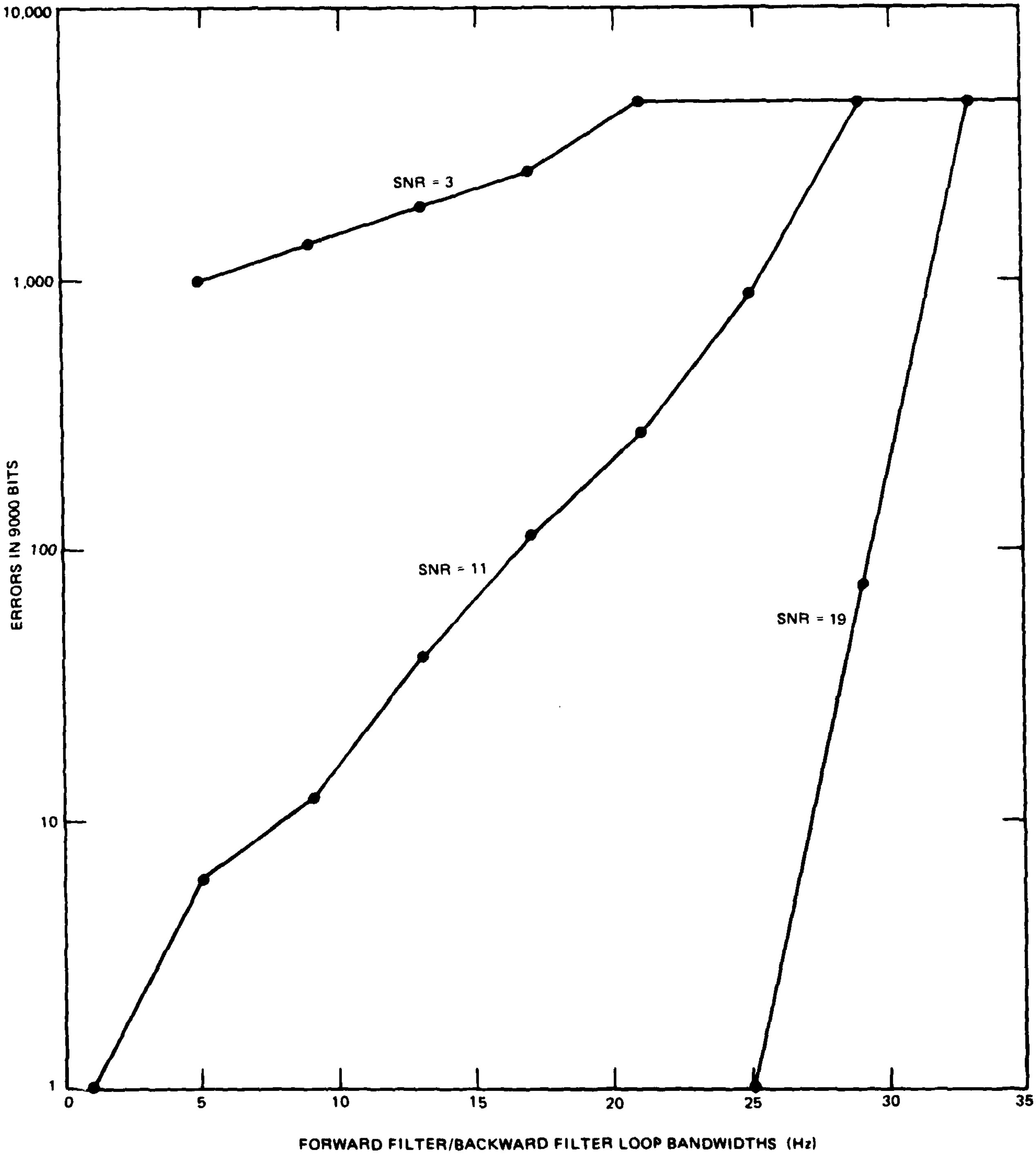

Figure 4. Performance of an adaptively (LMS) equalized receiver having eight forward and four backward taps. Compare with figure 5 which shows effects of more taps. Channel: one fixed path.

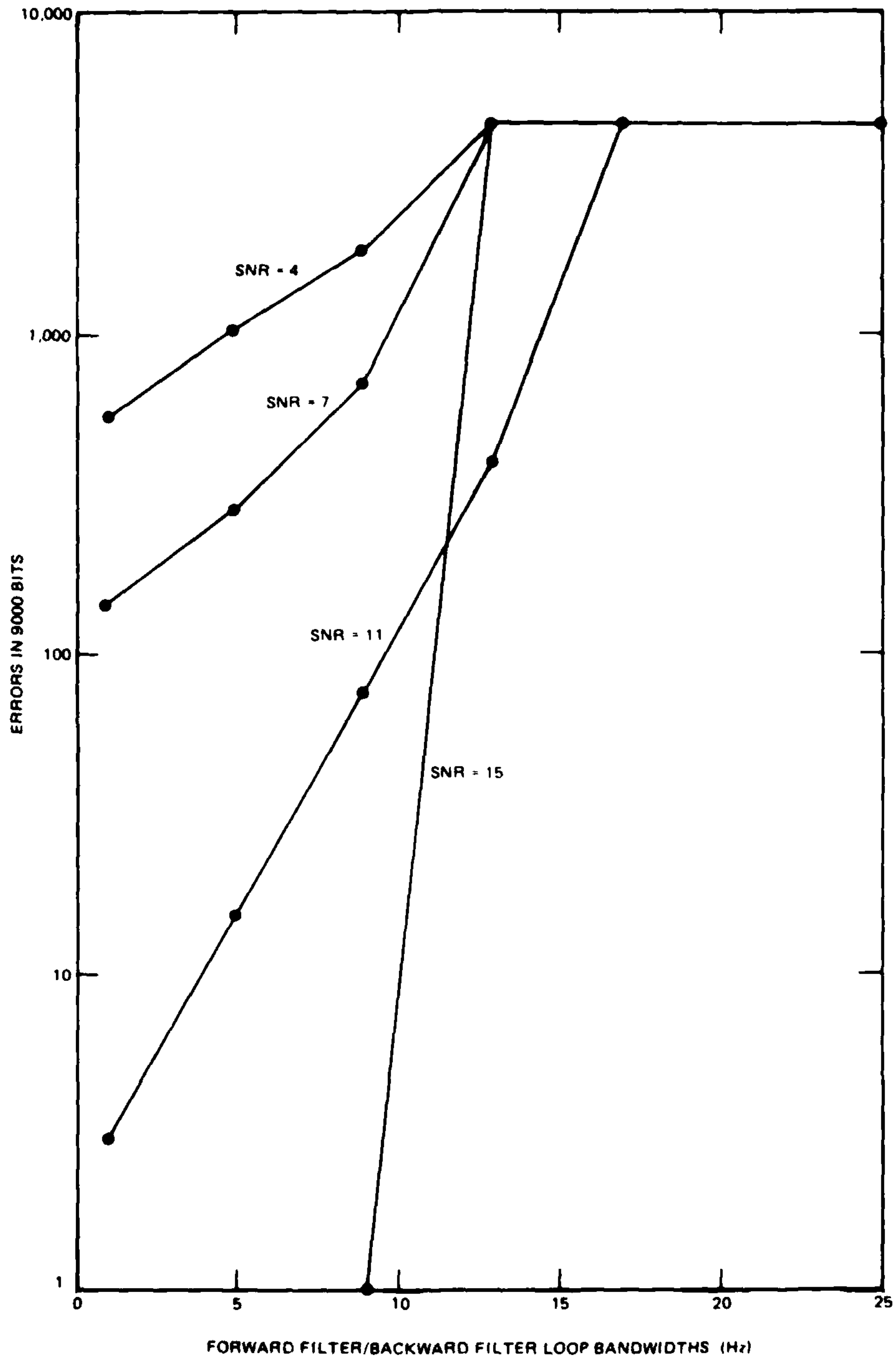

Figure 5. Performance of an adaptively (LMS) equalized receiver having fifteen forward and six backward taps. Compare with figure 4 which shows effects of less taps. Channel: one fixed path.

SIGNAL-TO-NOISE RATIO, dB

NB-QPSK receiver configuration	3, 4 dB	11 dB	19 dB
15 forward taps 6 backward taps All tap weights initially (0, 0)	9 Hz	13 Hz	9 Hz
8 forward taps 4 backward taps All tap weights initially (0, 0)	17 Hz	25 Hz	17 Hz

Table 1. Maximum filter loop bandwidth, Hz, where receiver was still stable. Forward and backward filter loop bandwidths were equal. Runs were made at loop bandwidths of 5, 9, 13, 17, 21, 25, and 29 Hz. The channel was one nonfading path (taken from figs 4 and 5).

The Kalman and LMS loop bandwidths were studied with channels having fading paths (fig 3 and 6). With fading channels output bit error rate increases with low as well as with the excessively high equalizer loop bandwidths. The bit error rate increases at low filter loop bandwidths because of the inability of the filter tap weights to change as fast as the channel. At high loop bandwidths, the bit error rate increases because of excess noise in the filter feedback loop. With very rapid adaptation, the time constants of the filter are so short that random noise is not averaged out and can affect the tap weights.

The number of weights which are to be estimated affects the speed with which weights converge to the correct value. With a rapidly changing channel the weights may not be able to converge to the correct value before they have changed significantly. Simulations were run to see how many weights one can use and still keep up with a rapidly fading channel. It was found that the allowable number of weights is small and requires one to use something other than a densely tapped delay line if the relative path delay is long and/or the sampling rate is high.

In an experiment where the number of taps in a LMS equalizer was increased from 2 forward/4 backward (fig 2) to 12 forward/6 backward (fig 7), the maximum usable equalizer forward/backward loop bandwidth was found to drop from about 27 Hz to about 10 Hz. The range of usable loop bandwidths decreased rapidly as the number of taps increased. This is crucial as these loop bandwidths and numbers of taps are of the same magnitude as those needed to follow rapidly changing channels with a few milliseconds delay between paths and a receiver sampling rate of 2400 samples per second. Twelve taps is not enough to densely tap a channel with a few milliseconds path separation if the signal is moderately wide band and requires sampling a few times higher than 2400 samples per second.

Ideally, one would like to have a receiver which once set up would work with all channels. Equalizer loop bandwidth is one parameter for which one can choose a value satisfactory for a range of channels. Figure 1 shows bit error probability as a function of LMS loop bandwidth for fade rates of 0.0 to

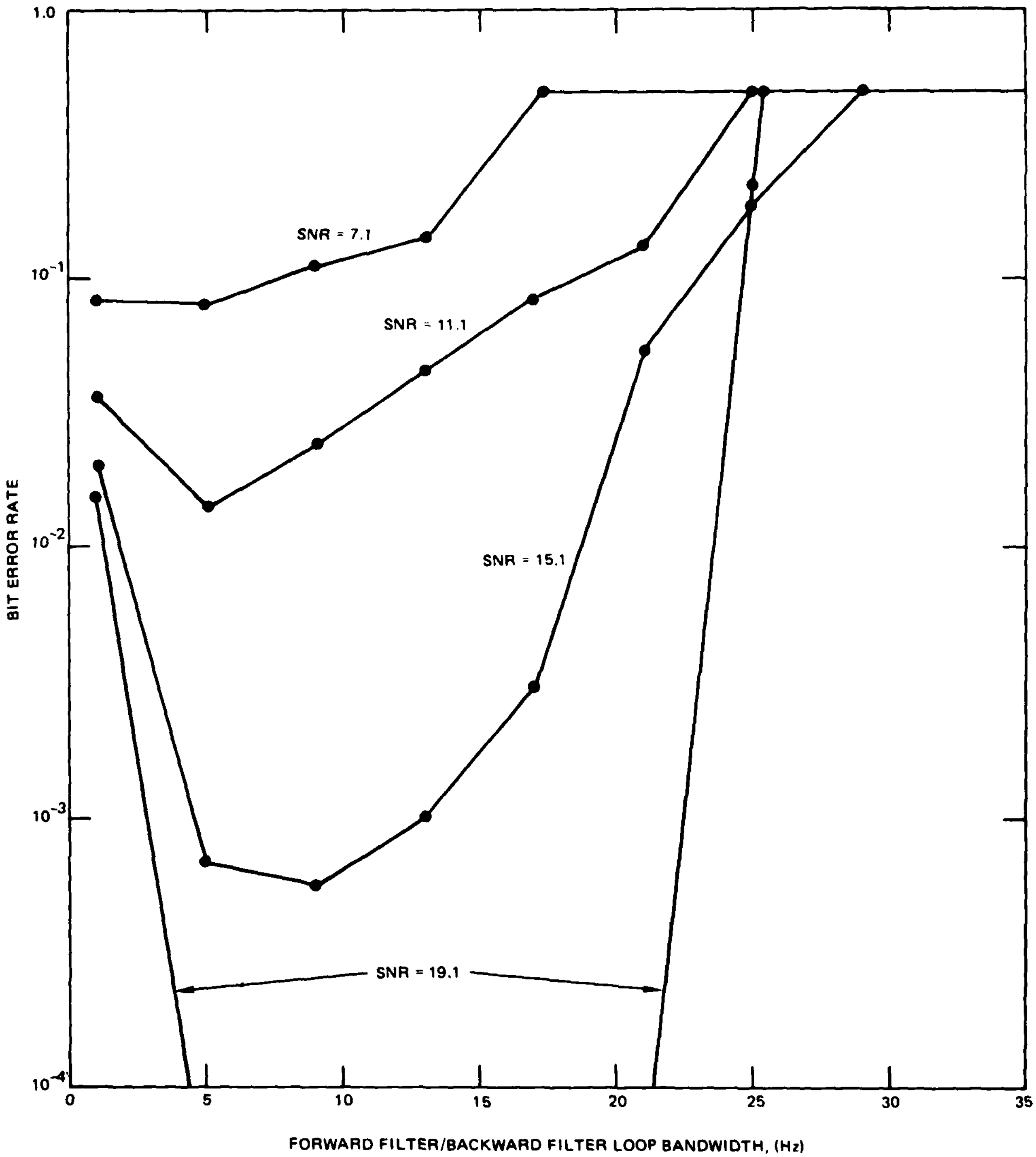

Figure 6. Performance of an adaptively (LMS) equalized receiver having six forward and four backward taps on a fading channel. Compare with figure 7 which shows the effects of more taps. *Channel: two equal* average power paths. One path fixed and the other fading with 1 Hz frequency spread.

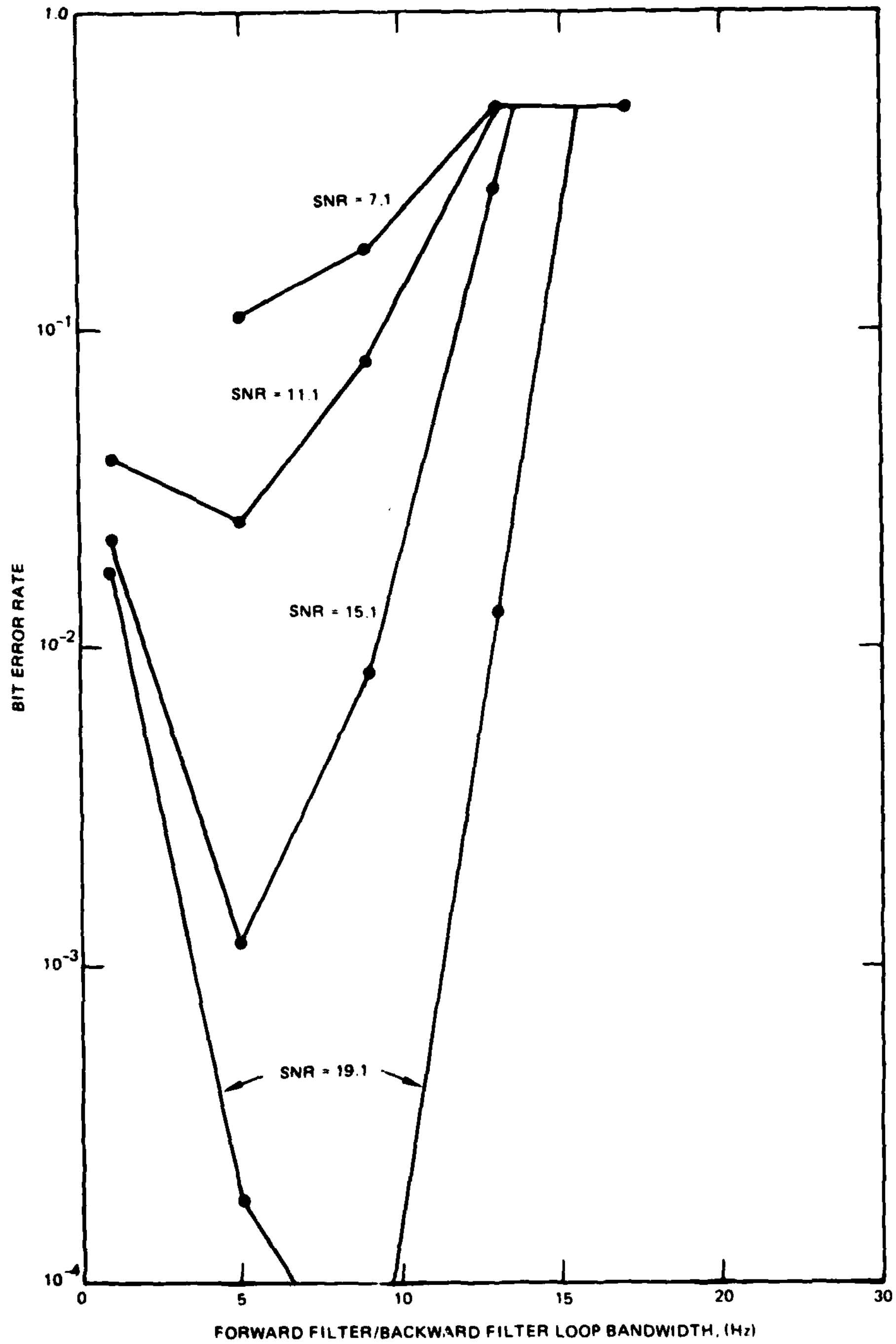

Figure 7. Performance of an adaptively (LMS) equalized receiver having twelve forward and six backward taps on a fading channel. Compare with figure 6 which shows the effects of less taps. Channel: two equal average power paths. One path fixed and the other fading with 1 Hz frequency spread.

0.5 Hz. If one uses the optimal loop bandwidth for 0.5 Hz, the performance is also quite good, though not optimal, for channels with lower fade rates. This is true for both the Kalman and LMS based equalizers. A qualification needs to be made that the LMS algorithm has problems with multiple fading paths, probably because on occasion the eigenvalue spread gets very large.[4]

The importance of Kalman filter loop bandwidth is shown in figure 8. The channel which was used for the series of tests had two paths having equal average power and a doppler spread of 1.0 Hz. The paths, separated by 1.0 ms Kalman filter loop bandwidth (KFLB), become especially important when Eb/No is greater than about 20 dB. Figure 2 shows that as Eb/No goes up, the optimal value and maximum usable values of KFLB increases. This is because as Eb/No goes up, less data samples are necessary to get a high quality estimate of the input covariance matrix. At high SNRs, high KFLB is necessary to keep the weight misadjustment down and to keep the performance curves from leveling off (fig 8). At high SNRs the covariance matrix can be accurately estimated using very little data without fear of corruption by noise. This is necessary if one is to accurately follow a very rapidly changing channel with very high accuracy.

2.3 FILTER TAP POSITIONING

The traditional tapped delay line equalizer has a tap at every position on the delay line (table 2). This strategy can result in an excessive number of taps. For instance, a moderate wide band signal requiring a sample every 0.1 ms would require 21 taps on a densely tapped delay line to equalize signals with a 2.0 ms separation. It was shown in the previous section on equalizer loop bandwidth that equalizers with 21 taps can't keep up with a rapidly fading channel. Another problem is that the more taps one has on the delay line, the faster the digital hardware has to be to implement the weight update algorithms. The number of computations required per second is pushing the limits of the possible with general purpose array processors, even if one only has a few taps on the delay line. Since the compute time is proportional to

[4] Monzingo, RA, and Miller, TW, Introduction to Adaptive Arrays, p 543, John Wiley and Sons, 1980.

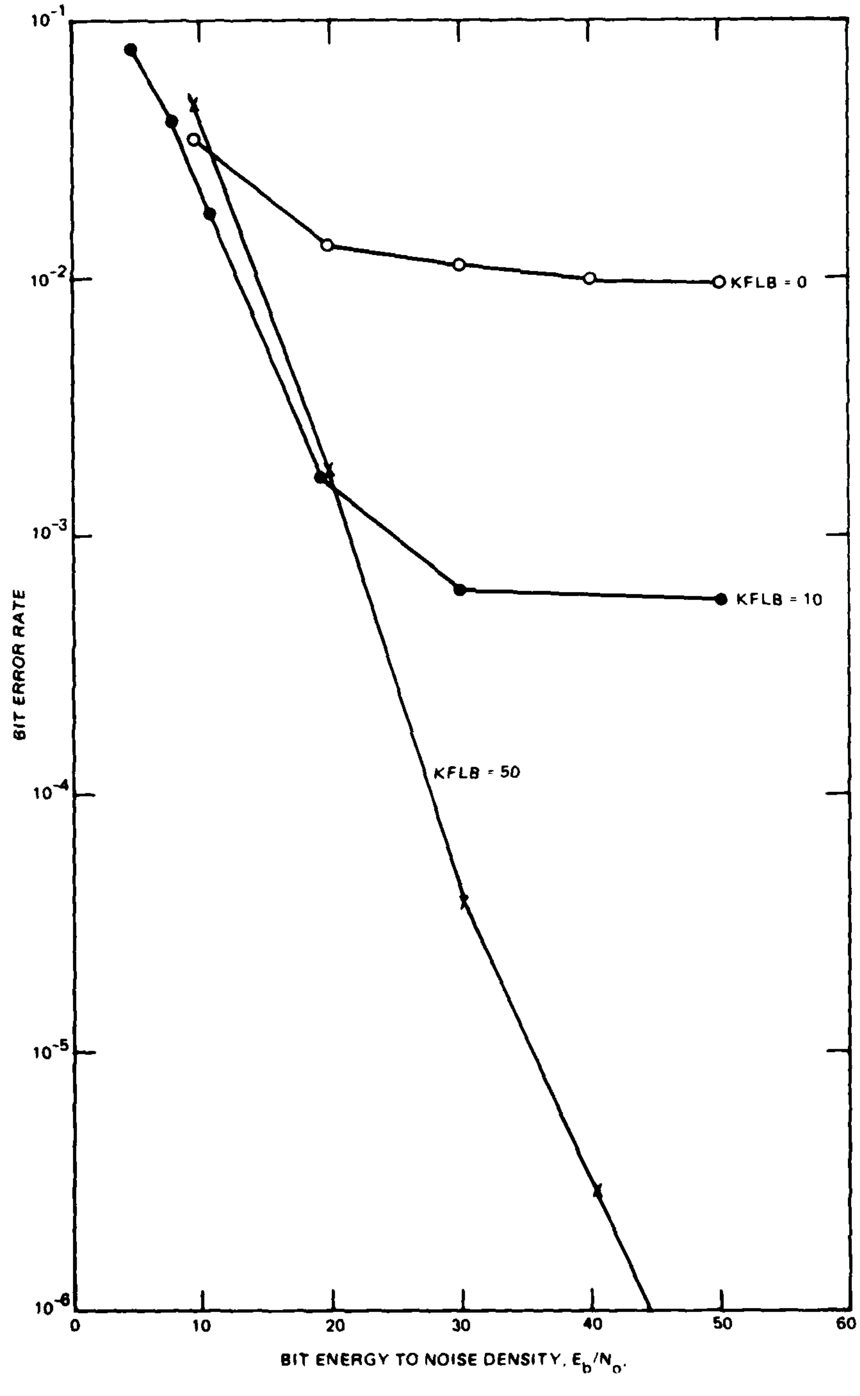

Figure 8. Effect of equalizer loop bandwidth on the performance of an adaptively (Kalman) equalized receiver given a channel with two equal average power fading (1 Hz frequency spread) paths.

Receiver samples delay	0	1	2	3	4	5	6	7
Channel impulse response								
Clustered taps	0	1	2			5	6	7
Dense taps	0	1	2	3	4	5	6	7

Table 2. Tap positioning.

the square of the number of taps for the Kalman algorithm and directly proportional to the number of taps for the Kalman algorithm, the situation rapidly gets worse as the number of taps goes up.

Two tap positioning strategies were tested, dense and clustered. When properly set up, good results were obtained with both techniques. Clustered tapping requires more knowledge of the channel. Dense tapping was characterized by the presence of a tap on every position in the filter delay line (table 1). Clustered tapping was characterized by small portions of the delay line being densely tapped while the rest of the delay line had no taps. Since clustered tapping does not require increasing the number of taps as the multipath spread increases, clustering can be held down to the number of weights to be estimated. The clusters were positioned so that if a properly synchronized channel impulse response was in the delay line, each peak, which corresponds to a path, was centered in a cluster of taps. Clustering of taps can work because the channel's path delays are essentially constant for the duration of a message. The number of taps per cluster (path) can be as small as two.

Clustered tapping has a weakness in that clusters are positioned on the basis of the channel conditions during a preamble. Therefore, any path faded out during the preamble will not be assigned a cluster of taps and when the path returns it cannot be equalized. Methods of dealing with paths that appear after the start of a transmission need to be investigated. Dense tapping has an advantage over clustered tapping in that it can accommodate paths that appear during the message, as long as their delays fall within the bounds of the tapped delay line. This may be an important property, especially for narrow band, where densely tapped delay lines can be several milliseconds long with relatively few taps.

2.4 SYNCHRONIZATION PROBLEMS

There are problems in synchronizing the DFE receiver when the received signal consists of fading multipath. If during the signal preamble, one of the paths is temporarily faded out, taps may not be properly positioned to equalize that path when its signal power increases. Of special concern are the earliest and latest signals because even when using dense tapping strategies such signals may fall outside the limits of the equalizer's tapped delay line. If these paths are not equalized when their power becomes significant they will cause intersymbol interference and errors. But if the impulse response of a new signal path falls within the limits of a densely tapped delay line, taps will be waiting for it. Unfortunately, one can't just use very long densely tapped delay lines as protection against all possibilities. It was shown in the section "Adaptation Loop Bandwidth" that the price of many taps is reduced maximum filter loop bandwidth and less ability to follow rapidly fading channels.

Some ways of determining when and where to add taps to the delay line during a transmission might include: (1) partition the message into packets short enough so that the channel is unlikely to change significantly during the packet and insert a known sequence for probing the channel at the head of the packet; and (2) use residual error examination techniques to detect new delay line positions requiring taps. Initial examination of option (2) showed promising results.

3.0 PERFORMANCE ON SIMULATED CHANNELS

3.1 EQUALIZATION OF MULTIPATH COMPARED TO DIVERSITY

Several experiments were conducted to discover how the narrow band decision feedback equalizer processes multipath signals. If two paths are present, does the DFE combine the energy or does it use the energy of one path and cancel the other? It was found that the decision feedback equalizer performs as if it has switching diversity.

The first test to determine what kind of diversity that the DFE receiver had involved comparing its performance on a channel with one nonfading path to its performance on a channel having two equal, nonfading paths. The signal power of each of the paths equaled the power of the single path channel. An equalized receiver configuration was chosen which could handle one or two paths. It was discovered that with a two path channel, the performance was the same as with just one path (fig 9, curves 1 and 2). This showed that the equalizer was not using the sum of the path signal powers to produce the equalizer output. If it had been, the two-path case should have performed 3 dB better than the one path case. The experiments were run with both sparse and dense tapping with no difference in the results. The above experiment was also run using both Kalman and LMS weight adaptation with no significant difference.

A test was conducted to determine whether or not the DFE receiver was using the first arriving path and canceling the other paths. The test, similar to the above, was conducted with two fixed paths where the second path was 1.26 times the first path (fig 9, curve 3). The second path's amplitude gain was approximately 2 dB stronger than the first path's gain and the sum was approximately 4 dB stronger than that of the first path. The probability of error versus signal-to-noise ratio curve improved by about 1 dB as compared to the results for the first path alone. This result supports the hypothesis that the narrow band DFE receiver uses the strongest path and cancels the others even if the strongest path is not the earliest arriving path.

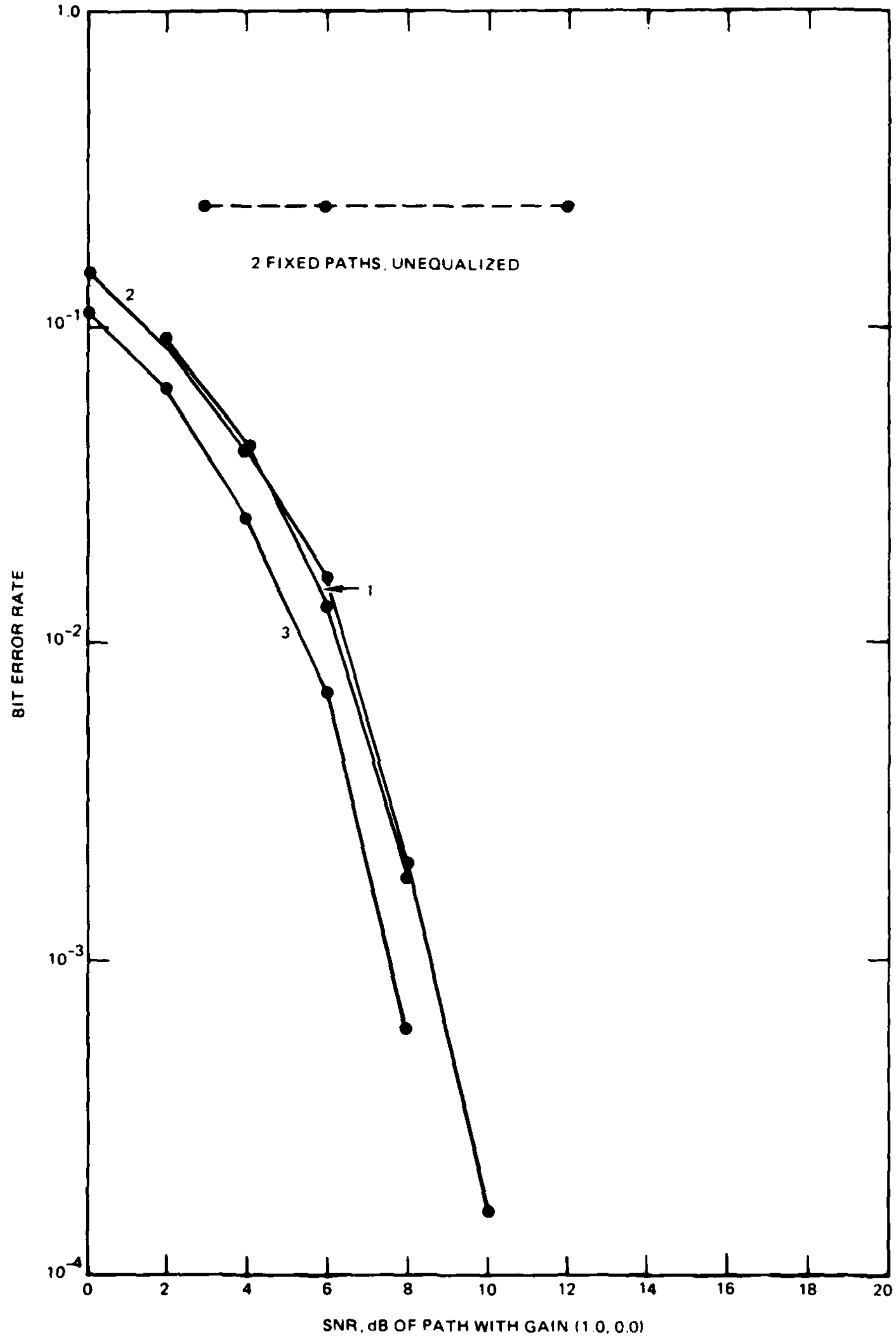

Figure 9. Effect of relative path strengths with a multiple path channel on narrow band, LMS, DFE performance.

Curve 1: One fixed path with complex gain (1,0).

Curve 2: Two fixed paths with complex gains (1,0), (1,0), and 2.5 ms separation.

Curve 3: Two fixed paths, path one with gain (1,0), path two with gain (1.26,0) and 2.4 ms delay.

If the narrow band DFE uses the strongest path and cancels the others, for reliable communications, there needs to be at least one sufficiently strong path regardless of the total signal power available. As the number of paths increase, the probability that they will all be faded out at any one time goes down, but also the percentage of the total power in any one path goes down. Figure 10 compares the performance of the Kalman DFE on a channel with two fading paths with a channel having three fading paths - all paths having a doppler spread of 1 Hz. The performance with three paths is better than with two paths and the difference increases as the SNR increases just as one would expect if the equalizer is able to utilize channel diversity. The LMS algorithm was also tested against these same two and three path fading channels but was found to perform poorly (fig 11). At low SNRs the LMS algorithm performed similarly to the Kalman with the three-path channel causing less errors than the two-path channel. At high SNRs the three path channel became unstable and the performance with the two path channel leveled off. The leveling off probably results because the rates of adaptation of the forward and backward filter cannot be set high enough to handle the rapid fading and wide eigenvalue spread[5] without causing the equalizer to become unstable.

3.2 PATH SEPARATION

A series of simulations was conducted using LMS weight adaptation to determine the effect of varying the relative multipath delay on the narrow band decision feedback equalizer. The performance curves (fig 12) appear to form three groups: (1) zero delay; (2) delays between zero and one bit; and (3) delays greater than or equal to one bit. Of the two cases with less than one bit delay, the zero delay performance did not level off at high SNRs, whereas, when the delay was between zero and one bit, the performance did level off. Decision feedback equalizer performance was best for delays of greater than or equal to a bit.

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[5] Monsen, P, and Parl, S, "HF Channel Adaptive Equalization Algorithm: Interim Technical Report", prepared by Signatron, Inc. for the Naval Ocean Systems Center under contract N66001-77-0248, December 2, 1977.

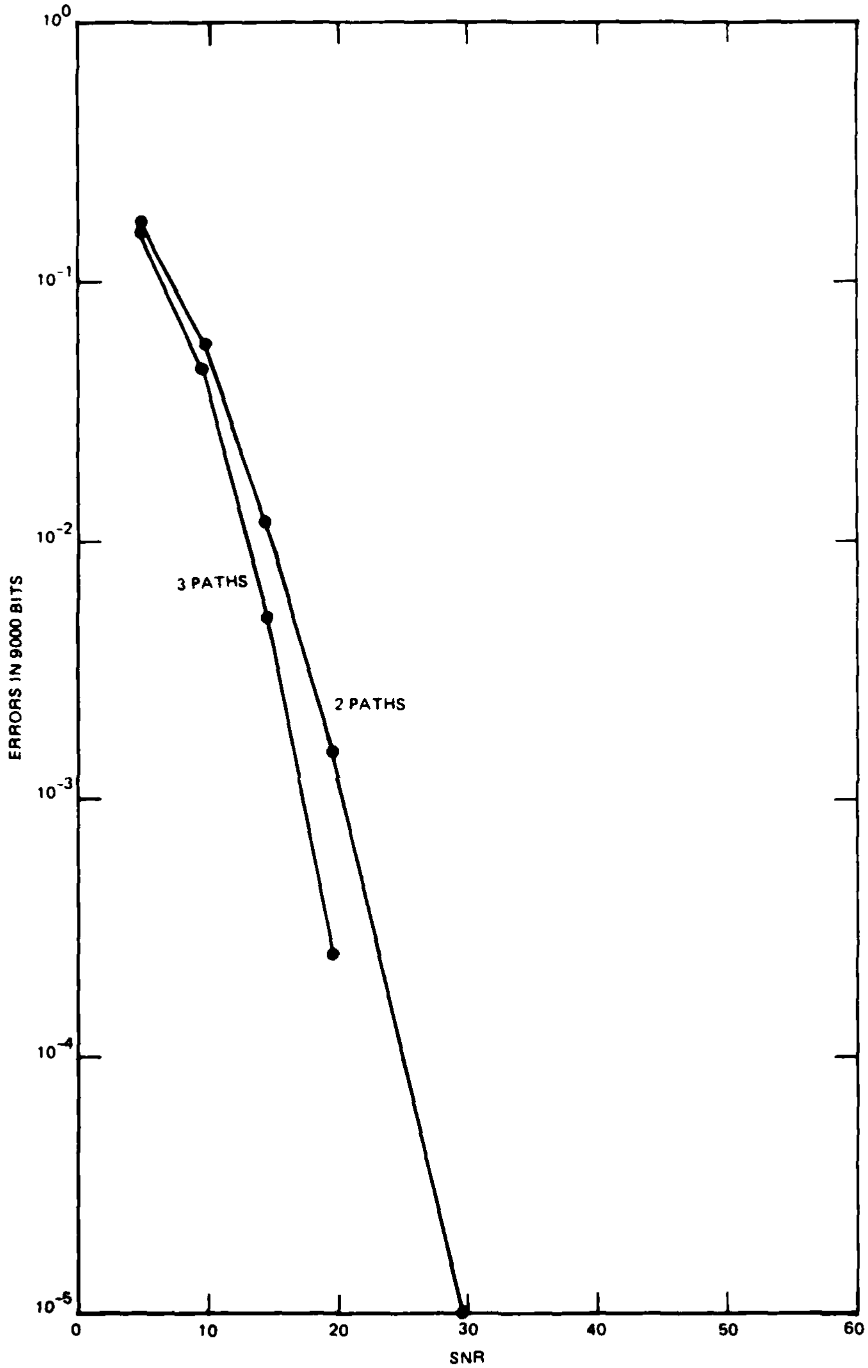

Figure 10. Effect of multipath diversity on Kalman DFE performance when the number of paths is increased. All paths have equal average power and fading.

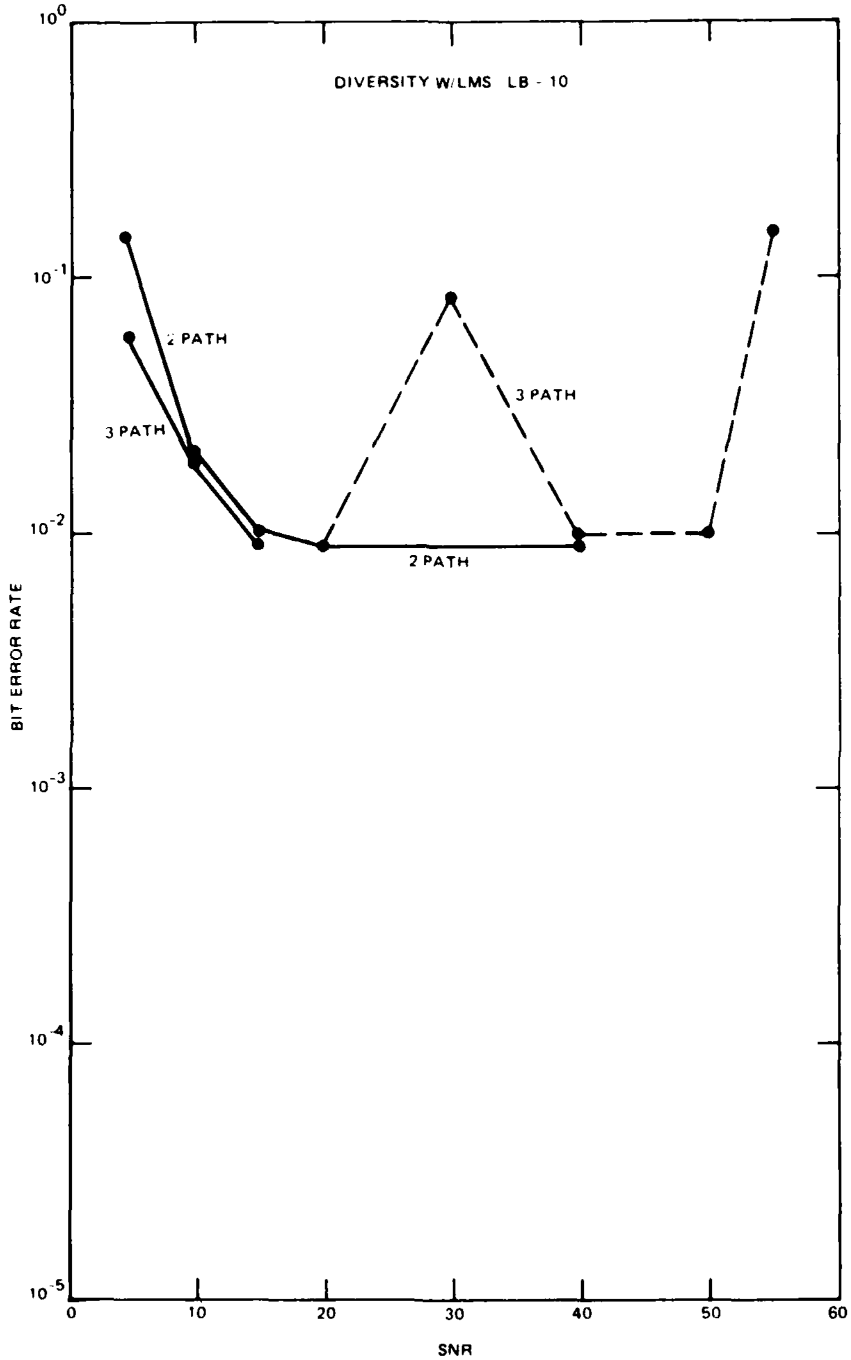

Figure 11. Effect of multipath diversity on LMS DFE receiver performance when the number of paths is increased. All paths have equal average power and fading.

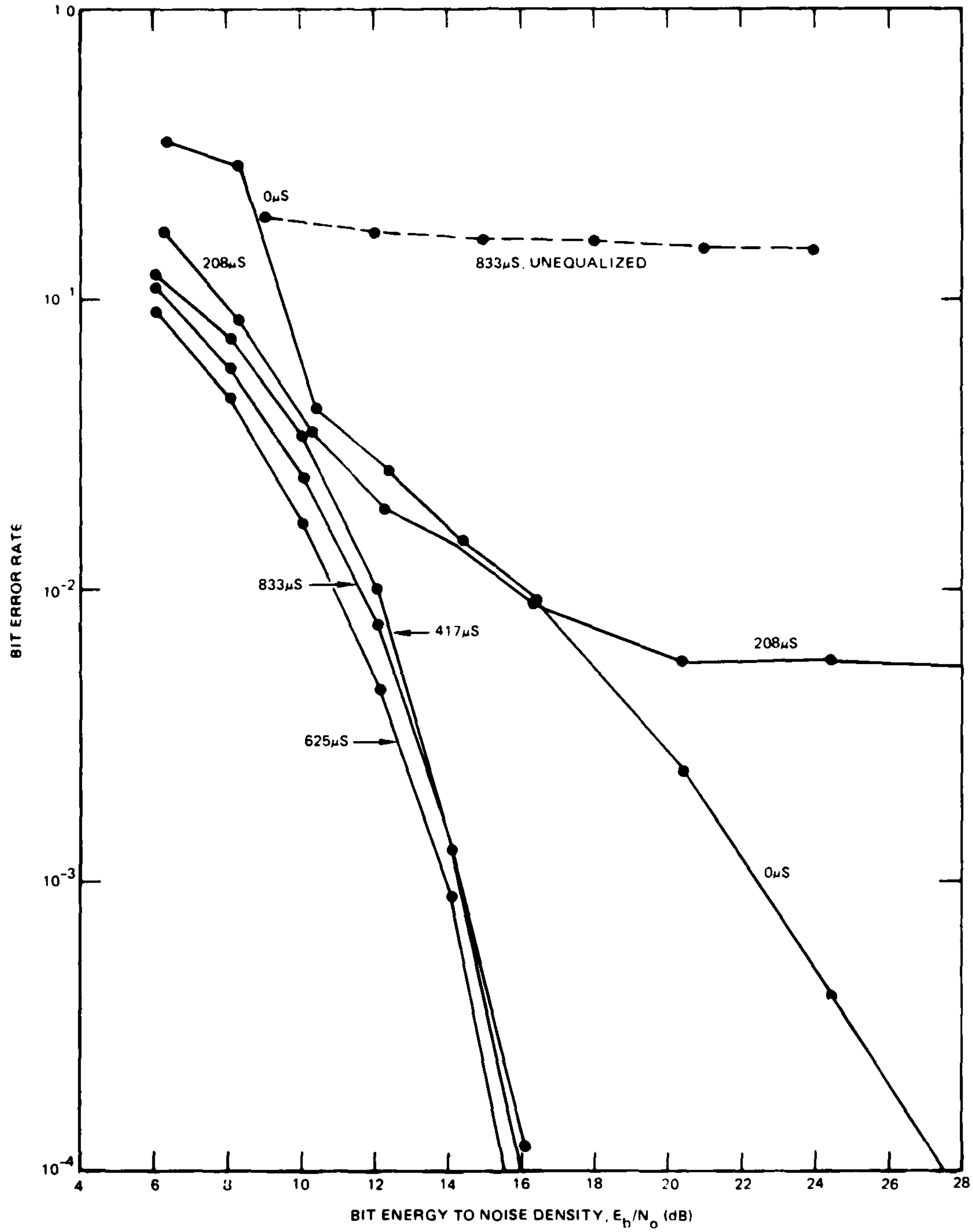

Figure 12. Effect of path separation on narrow band LMS DFE receiver performance curves. Channel: one fixed path and one path fading with 1 Hz frequency spread.

The performance of the equalizer with spread spectrum gain and varying multipath delay was examined briefly. The tests showed that spread spectrum gain modifies the behavior of the equalizer. Sometimes the spread spectrum equalizer's performance improved dramatically as the delay exceeded a chip and sometimes the performance curve did not show any major improvement until delays were greater than a bit period. The relationship between bit error rate, path separation, and spread spectrum gain was not clear.

4.0 PERFORMANCE ON MEASURED HF CHANNELS

4.1 SIMULATION OF REAL HF CHANNELS MEASURED BY CC WATTERSON

Channel simulations reported upon to this point have been similar to short range paths typical of intratask force communications ranges. These channels tend to have simpler, well defined mode structures as compared to long range paths that are encountered on ship-to-shore communication links. In this section we examine DFE receiver performance with channels having the same statistics as two long range channels measured by Watterson. The channels characterized were overland between points separated by 1 294 km. Tables 3 and 4 show parameters for the Watterson channels simulated by the DFES program. Differences in the simulated and measured parameters are a result of the DFES program's rounding off time delay values and being unable to simulate fade rates below 0.01 Hz.

Figures 13 and 14 show performance curves for the LMS and Kalman algorithms for a simulated transmission of about 2 minutes. On channel Watterson I1, the Kalman and LMS performed almost identically and neither made any errors at high SNRs. But on the Watterson channel I2 - a more complex channel - the LMS algorithm, became unstable at high SNRs (fig 14). The problem with the LMS algorithm was also noted in the section: Equalization of Multipath Compared to Diversity. The Kalman made no errors on channel I2 at high SNRs.

4.2 KALMAN VERSUS LMS ON FIELD TESTS

A field test was run (NOSC TR 709) in which signals were transmitted approximately 135 nautical miles between Pt Mugu and Pt Loma along the California coast. At the receiver the signals were digitized for later off-line processing. Results from processing some of this data are shown in fig 15-19. It was found that except for very simple channels, the Kalman algorithm out performed the LMS algorithm. We only have limited measures of the channel conditions during the field test transmissions (table 5). In general it appeared that the relative performance advantage of the Kalman over the LMS increased when the channels had more paths, more widely spread paths, and faster fading paths. The differences between the two algorithms became

Path	Time Delay, ms		Relative Power		Frequency Shift, Hz		Frequency Spread, Hz	
	W*	S**	W*	S**	W*	S**	W*	S**
1a	0	0	1	1	0.0022	0.0022	0.0073	0.01
1b	0	0	0.96	0.96	0.017	0.017	0.0318	0.0318
2	250	208	0.49	0.49	0.0089	0.0089	0.144	0.144
3	1099	1041	0.116	0.116	-0.167	-0.167	0.340	0.340

Table 3. Simulation parameters for Watterson channel I1.

Path	Time Delay, ms		Relative Power		Frequency Shift, Hz		Frequency Spread, Hz	
	W*	S**	W*	S**	W*	S**	W*	S**
1a	0	0	1.0	1.0	-0.0008	-0.0008	0.0065	0.01
1b	0	0	0.72	0.72	0.0127	0.0127	0.0084	0.01
2	250	208	0.66	0.66	0.0159	0.0159	0.180	0.18
3	550	625	0.0437	0.0437	0.108	0.108	0.334	0.334
4	1076	1041	0.1414	0.141	0.118	0.118	0.336	0.336

Table 4. Simulation parameters for Watterson channel I2.

W* = Watterson channel from Watterson, CC, JR Juroshek, and WD Bensema. "Experimental Confirmation of an HF Channel Model." IEEE Transactions on Communications Technology, Vol COM-18, No 6, Dec 1970, pp 792-803

S** = Our simulation of Watterson channel

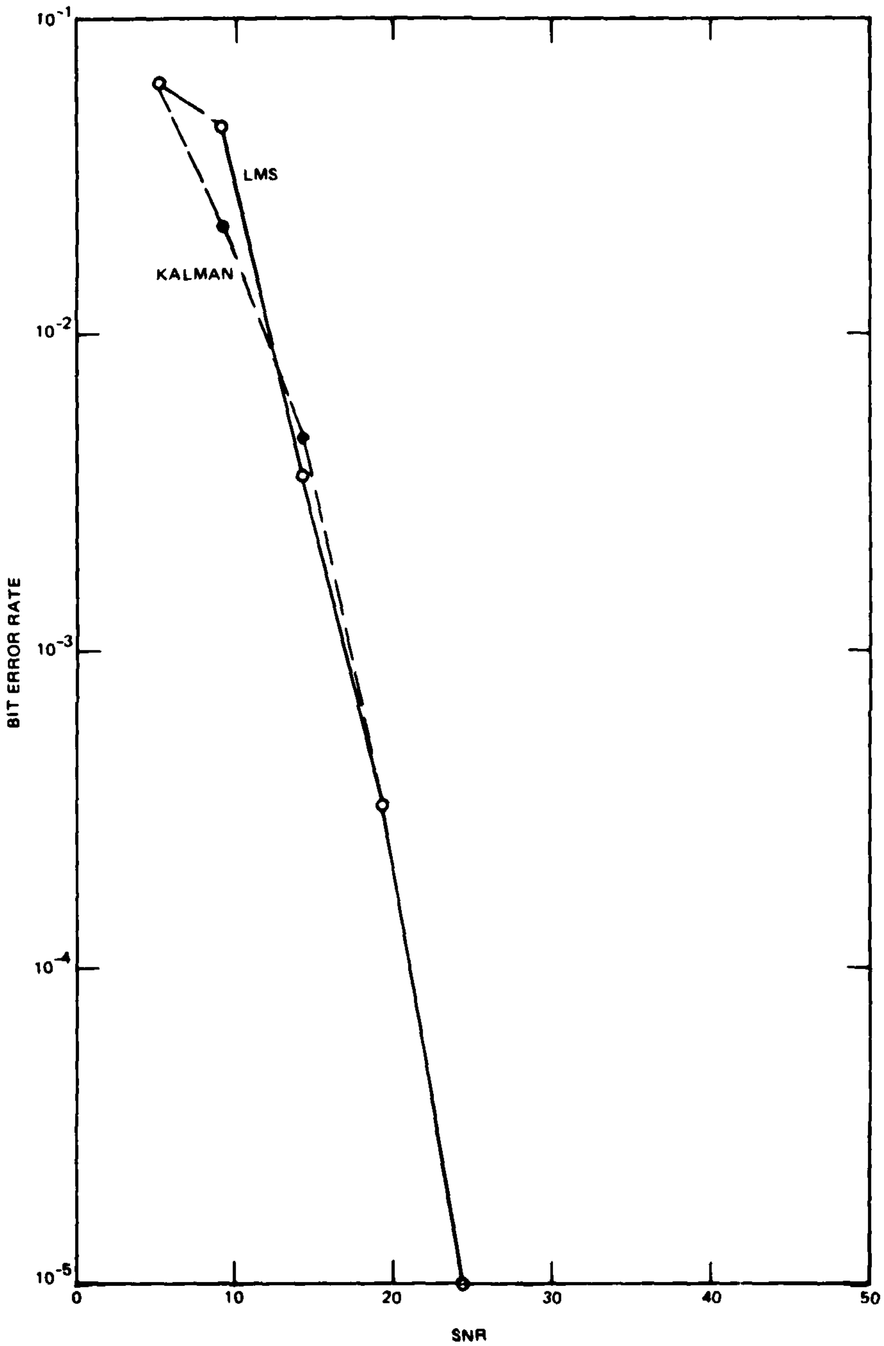

Figure 13. Comparison of receivers with Kalman and LMS adaptive equalization of Watterson channel II. Channel four fading paths. See table 3 for details.

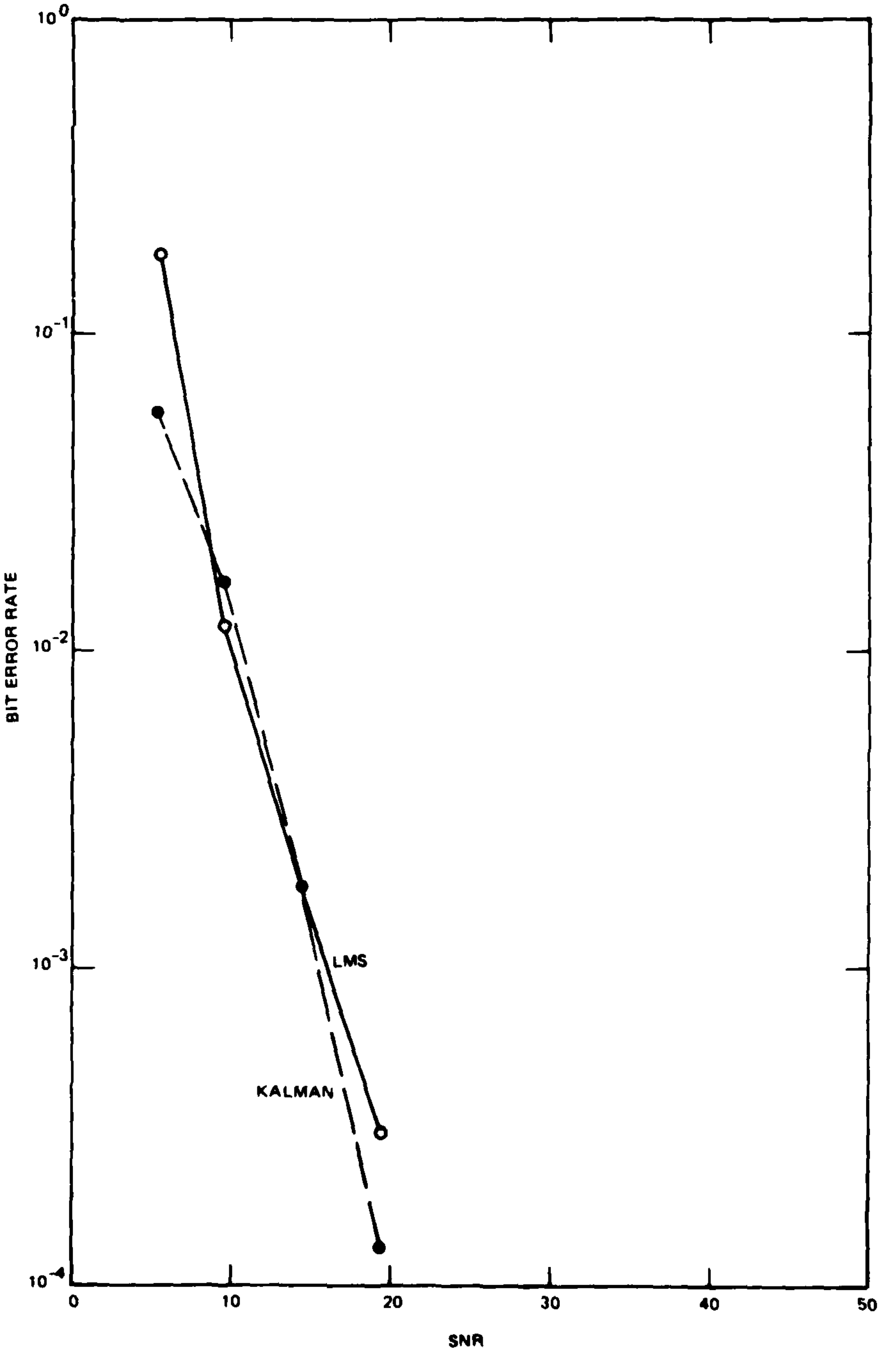

Figure 14. Comparison of receivers with Kalman and LMS adaptive equalization on Watterson channel 12. Channel: five fading paths. See table 4 for details.

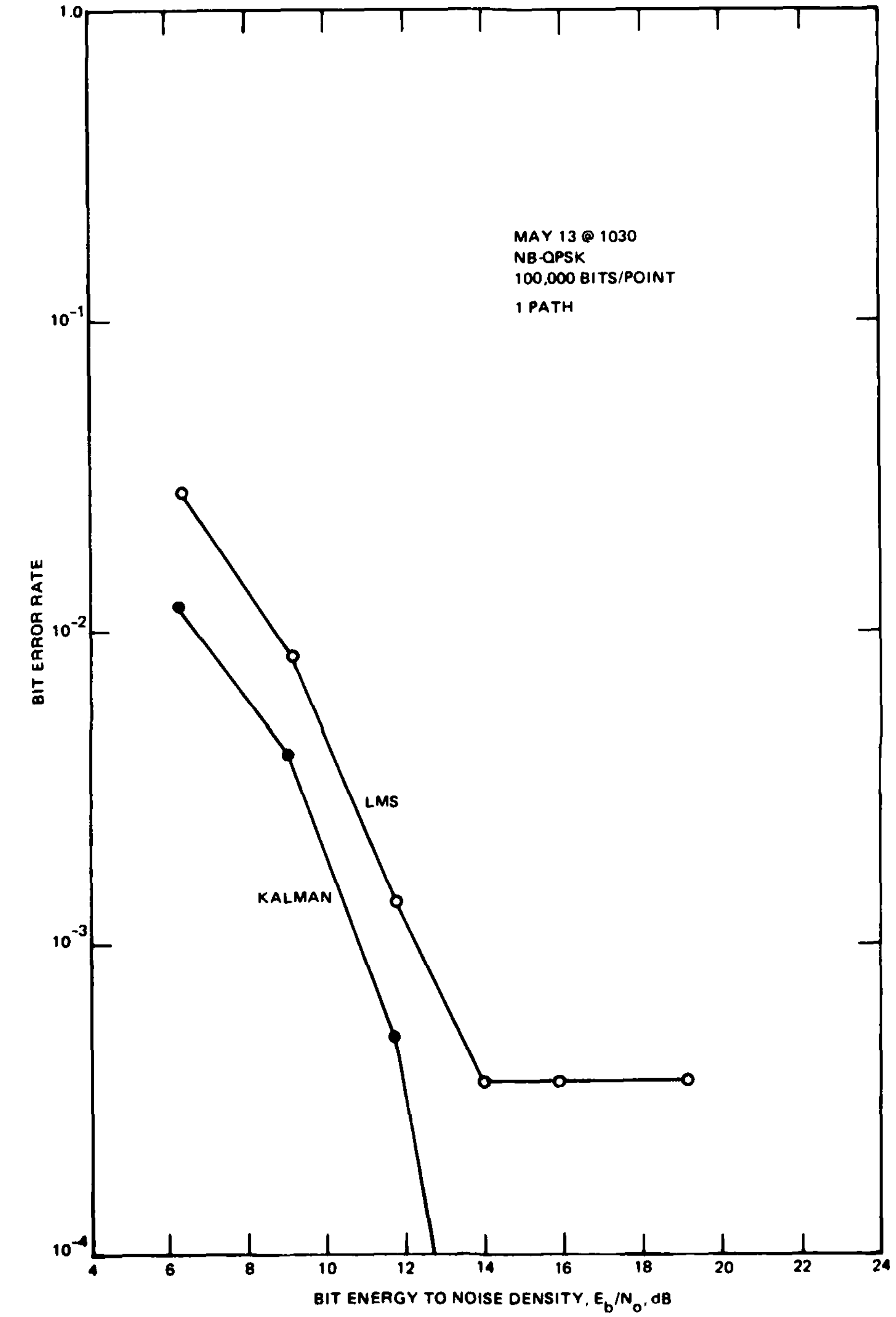

Figure 15. Comparison of DFE receivers using Kalman and LMS adaptation on transmission between Pt Mugu and Pt Loma. Channel: one fixed path. Characteristics summarized in table 5.

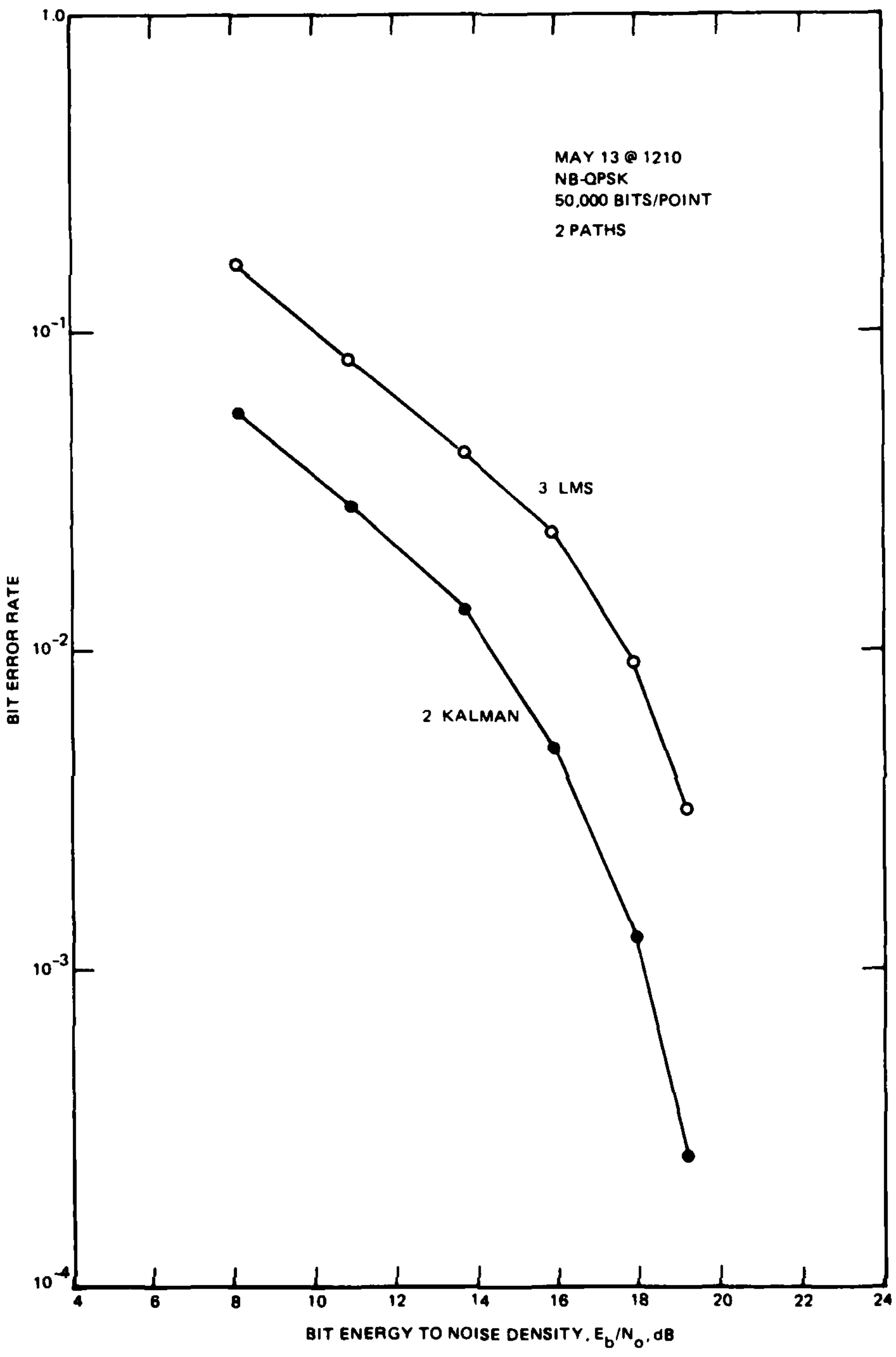

Figure 16. Comparison of DFE receivers using Kalman and LMS adaptation on transmission between Pt Mugu and Pt Loma. Channel: one fixed, one fading path. Characteristics summarized in table 5.

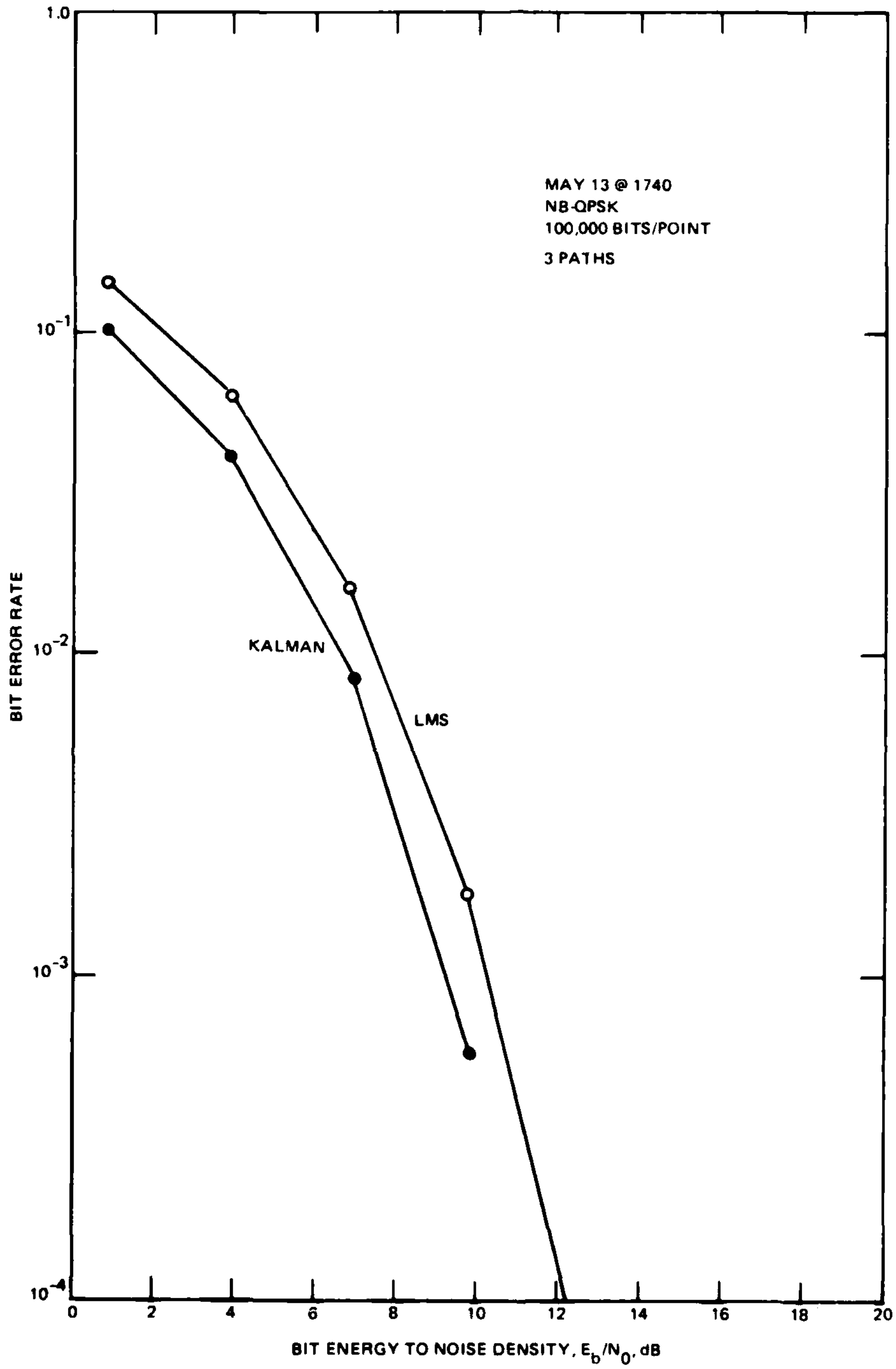

Figure 17. Comparison of DFE receivers using Kalman and LMS adaptation on transmission between Pt Mugu and Pt Loma. Channel: two fixed paths and one fading path. Characteristics summarized in table 5.

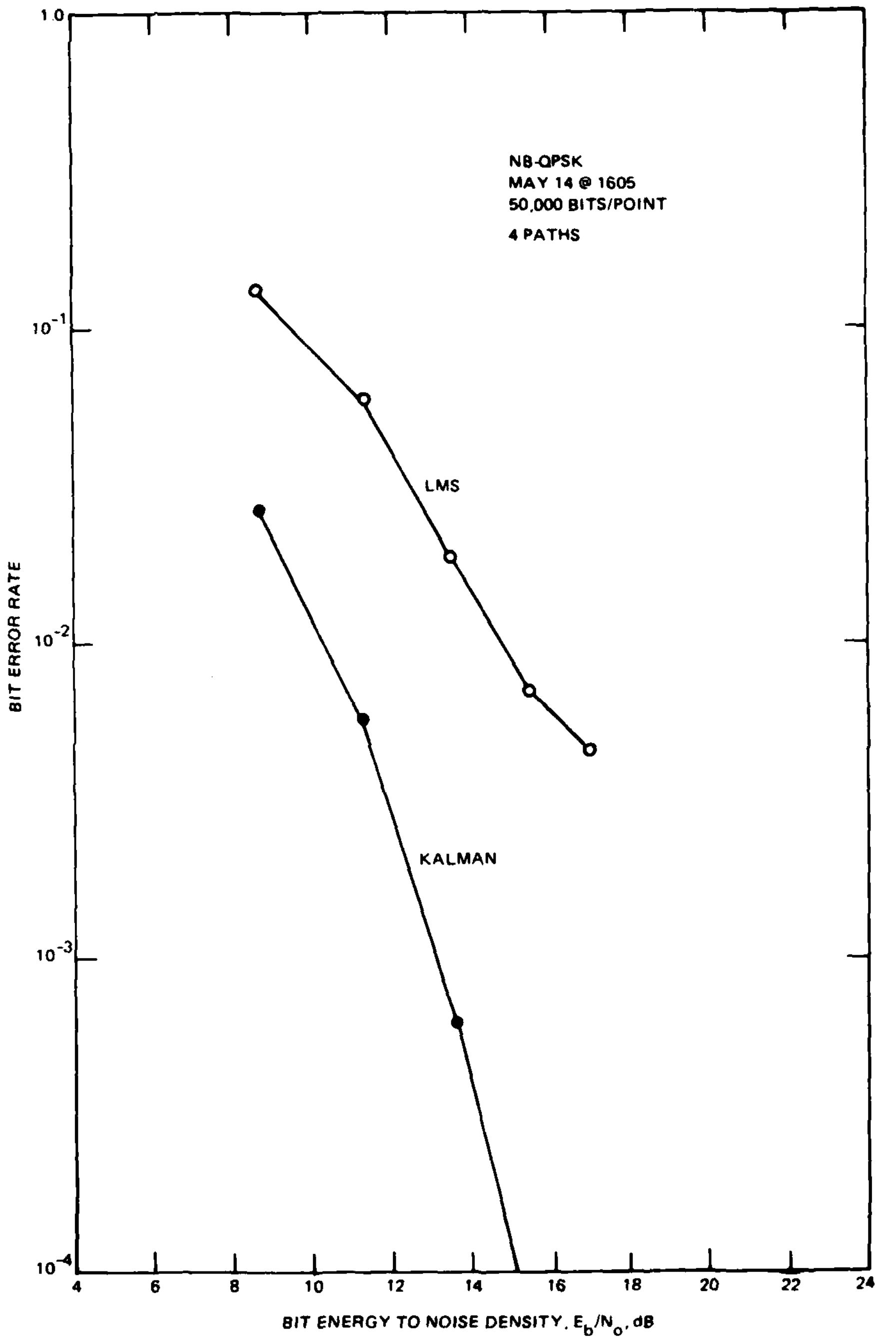

Figure 18. Comparison of DFE receivers using Kalman and LMS adaptation on transmission between Pt Mugu and Pt Loma. Channel: one fixed and three fading paths. Characteristics summarized in table 5.

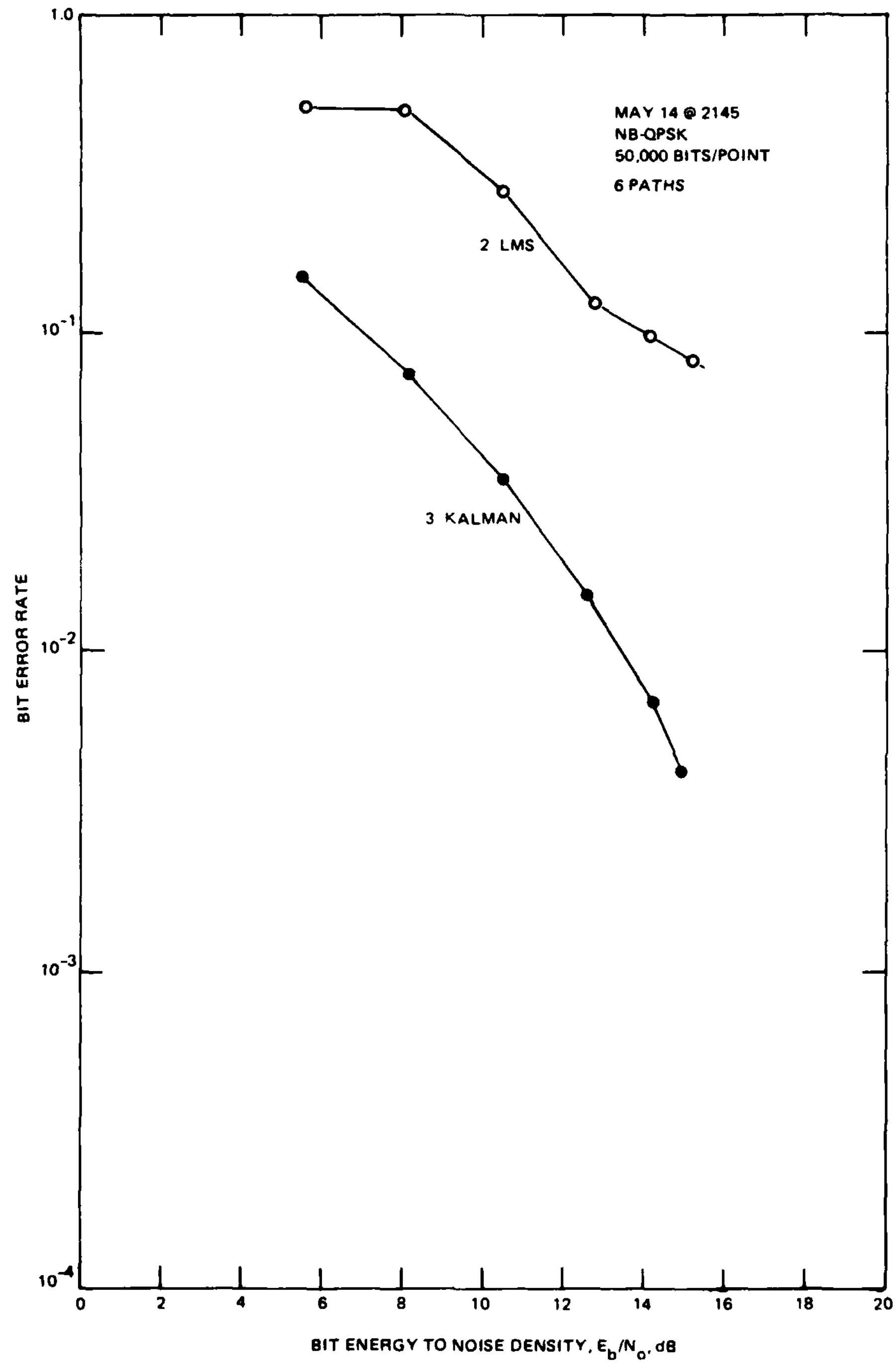

Figure 19. Comparison of DFE receivers using Kalman and LMS adaptation on transmission between Pt Mugu and Pt Loma. Channel: six paths. Characteristics summarized in table 5.

Figure #	Transmission Time	Relative Path Delay, ms	Relative Path Power, dB	Frequency, MHz	Tape (S+N)/N	Remarks
14	May 13 @ 1030	0.0	0	3.357	22.1	No fading
15	May 13 @ 1210	0.0	-10	6.835	24.4	0.3 ms delay path faded during transmission
16	May 13 @ 1740	0.0	0	5.785	27.3	0.0 & 0.3 ms delay paths steady, 1.2 ms path faded
		0.3	0			
		1.2	<-30			
17	May 14 @ 1605	0.0	0	6.835		-0.0 ms delay path not fading
		0.3	-28			
		1.4	0			
		3.6	-27			
18	May 14 @ 2145	0.0	0	5.785		
		0.6	-26			
		1.9	0			
		2.9	-20			
		4.2	-19			
		6.7	-20			

Table 5. Characteristics of channel while data were transmitted. All transmissions 135 nmi - Pt Mugu to Pt Loma. Narrow Band QPSK.

especially large at high SNRs. This result is in agreement with the simulation results when it was found that the LMS had problems with rapidly fading signals and when the SNR was above about 30 dB.

4.3 COMPARISON OF THE KALMAN DFE WITH PARALLEL TONE MODEMS

In order to get a feeling for how well the DFE receiver performs on difficult channels compared to some other receivers, a comparison was made with three parallel tone receivers tested by Watterson[6], (fig 20). One of the receivers, the MX-190, had error correcting coding. The simulations were all made with a two path channel with each path having equal average power, a fading bandwidth of 1.0 Hz, and a separation of 1.0 ms. At low SNRs the Kalman DFES performed as well as the best receiver that Watterson tested, (MX-190), and at high SNRs it performed even better. By choosing suitably high Kalman filter loop bandwidths, the BER for the equalizer continued to improve as SNR increased rather than leveling off as was the case with the other receivers.

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6 **Watterson, CC, "HF Channel-Simulator Measurements and Performance Analyses on the USC-10, ACQ-6, and MX-190 PSK Modems", p 206, Fig 85.**

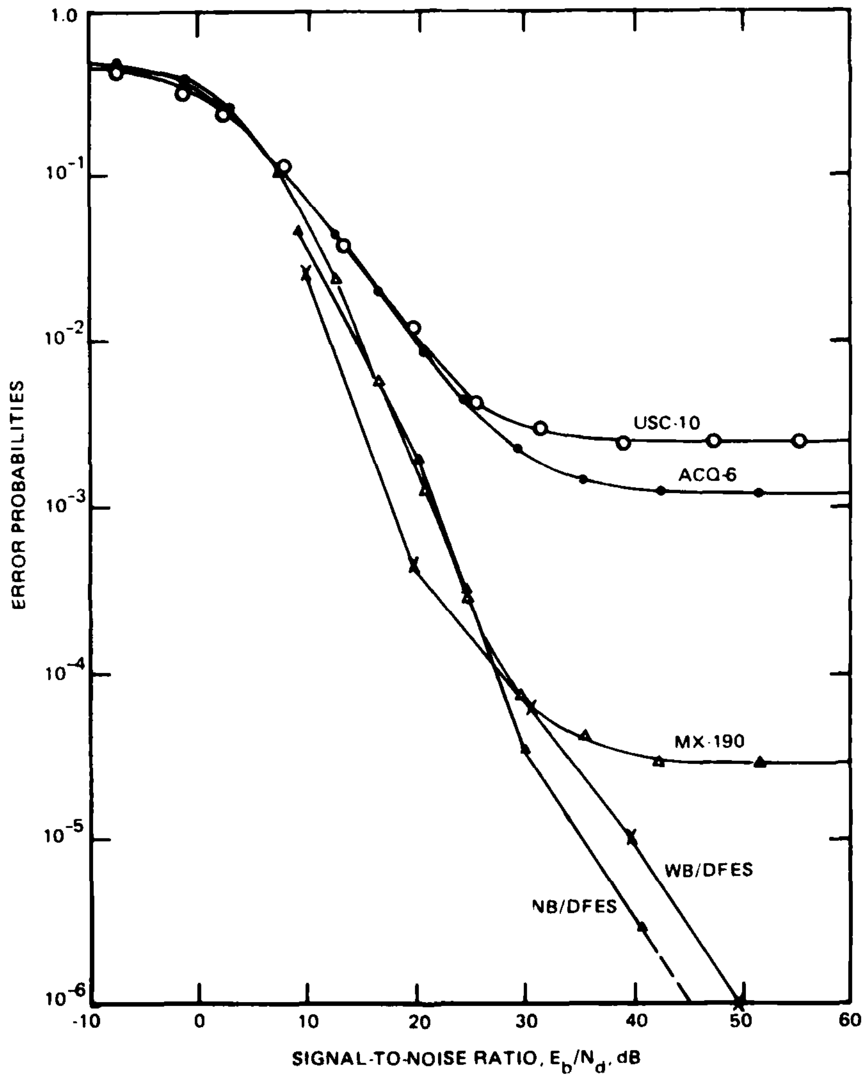

Figure 20. Comparison of two decision feedback equalized modems with three parallel modems (USC-10, ACQ-6, MX-190) tested by Watterson (6). The serial modems were narrow band (NB/DFE) and 40 chip/bit wide band (WB/DFE). The channel had two paths with equal average powers, equal doppler spread of 1 Hz, and a separation of 1 ms.

5.0 CONCLUSIONS AND RECOMMENDATIONS

We have demonstrated that when multipath is present, the decision feedback equalizer effectively equalizes channels with multipath, doppler spread, and doppler shift. To get a measure of how well the Kalman DFE receiver performs compared to some other receivers, performance curves were run on a channel used by CC Watterson to test several receivers. The test channel had two fading paths with 1.0 Hz doppler spread and equal average power. Using this test channel at low SNRs, the Kalman based DFE performed as well as the MX-190 PSK modem and at high SNRs it out performed the MX-190 and had bit error rates lower than 0.00001.

Since a DFE receiver using LMS weight adaptation would be simpler and cheaper to build than one using Kalman adaptation, a comparison of their relative performances was made on identical channels. The Kalman algorithm was found to out perform the LMS algorithm on most of our recordings of actual received communication signals and on simulated channels which had multiple fading paths. On very simple fixed channels the LMS algorithm could perform as well as the Kalman. These results are probably because of the LMS's poor performance on channels with large eigenvalue spreads.

On some channels with multiple fading paths, the LMS algorithm became unstable and receiver performance deteriorated as SNR increased to values above around 20-25 dB. Perhaps noise limits the eigenvalue spread at low SNRs and preserves stability, but as the SNR increases, the eigenvalue spread also increases and the channel becomes unstable.

The Kalman based DFE was easier to setup and run than the LMS based DFE as it was less sensitive to the value of filter loop bandwidth used as long as the value was large, 30-50 Hz. The LMS algorithm tended to be unstable at loop bandwidths high enough to equalize channels with multiple fading paths.

Sparse tapping of the equalizer delay lines was not only found to be possible, but necessary if one wants to use loop bandwidths high enough to follow rapidly changing channels when the path separation is greater than about 10 sampling periods. Sparse tapping enables the receiver to equalize chanels with long path separations with small number of taps.

Very short, as well as very long path separations can challenge the capabilities of an equalizer. With narrow band, the DFE equalizer performs worse when the path delay is less than a bit than when it is longer. This can be a problem with very long distance paths where the relative delays between the paths are smaller.

An examination of the narrow band DFE on multipath channels strongly suggests that it performs like switching diversity, ie, it uses the strongest path and cancels the others. This type of receiver is better than one that just picks one path and always utilizes it alone. But the performance is not as good as it could be if the receiver could recombine all of the received power into usable signal power. When the DFE equalizer was used with channels having several fading paths, it was found that performance was poorer than with simpler channels. This was probably because there were many paths contributing to the total received signal power, but the receiver was using only the strongest path.

A few areas of study on the DFE receiver which need more work include: (1) ability of wide band DFE receiver to resolve closely spaced paths; (2) performance of wide band DFE receiver on channels with all paths fading; and (3) different techniques for discovering new paths which appear during message transmission so that additional taps can be placed on sparsely tapped delay line to equalize them.

6.0 REFERENCES

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6. Watterson, CC, "HF Channel-Simulator Measurements and Performance Analyses on the USC-10, ACQ-6, and MX-190 PSK Modems", p 206, fig 85, July 1975.